Balance during obstacle crossing following stroke

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Abstract

Difficulty negotiating obstacles may contribute to the high falls rate following stroke. This study examined the impact of stroke on balance during obstacle crossing. Centre of mass (COM) and centre of pressure (COP) were measured as 12 stroke subjects and 12 unimpaired subjects stepped over a 4 cm high obstacle at self-selected speed. Unimpaired subjects also walked at speeds matched to their yoked stroke subject. Compared with unimpaired subjects at matched speed, at unaffected lead toe clearance, anterior–posterior (AP) separation between COM and COP increased in stroke subjects, which might indicate instability. Step lengths before and after the obstacle tended to be reduced which could increase the risk of losing balance forwards. The COM AP velocity was reduced at affected lead toe off following stroke, which may minimise instability. Following stroke the COM and COP were positioned more posteriorly during affected lead toe clearance, which might also assist stability.

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Keywords: Obstacle crossing; Stroke; Gait; Balance

Obstacle crossing is impaired following stroke [1] and may contribute to a high falls rate [2]. While lead and trail limb kinematics during obstacle crossing have been documented following stroke [3,4], balance deficits have not been quantified. A preliminary study showed that in people with stroke nearly half of the failed attempts to step over an obstacle were due to an inability to maintain balance [1]. While this indicates that people with stroke have impaired balance during this task, it is also possible that cautious or compensatory movement strategies might be used to reduce risk. The purpose of this study was to compare balance during obstacle crossing between subjects with stroke and unimpaired individuals and to identify gait patterns that may threaten or enhance stability.

Challenges to balance during obstacle crossing are additional to those documented for unobstructed walking [5]. Increased swing limb elevation during obstacle crossing increases the balance demands [6,7]. Balance requirements also vary throughout the crossing stride [8]. During lead limb clearance, the centre of mass (COM) moves away from the base of support (BOS) and there is little time to reposition the foot if the lead limb contacts the obstacle. During trail limb clearance, the COM moves towards the BOS and there is greater time to modify the foot trajectory in the event of foot contact, so control of balance is less critical. Hence, balance was examined during both lead and trail limb clearance.

Several variables have been used to quantify balance during walking and obstacle crossing [5,7,9–12]. The
COM velocity in the anterior–posterior (AP) and mediolateral (ML) directions is important when considering the stability of dynamic tasks [13,14], including obstacle crossing [7,9,15,16]. In healthy subjects, the velocity of the COM in the AP direction is reduced with increasing obstacle height [7]. Older people with balance problems and people with a traumatic brain injury (TBI) demonstrate greater peak COM velocities in the ML direction [15,16]. Separations between COM, centre of pressure (COP) [5,10–12,17] and the BOS [7] have also been used as indicators of balance. The AP separation between COM and COP is increased as obstacle height increases [7], and reduces with age [11], while ML separation is increased in subjects with TBI [16].

Spatial and temporal variables also provide information about balance. Step length and width indicate the size of the BOS and approximate position of the COP, as during single limb support the COP must lie within the foot [18]. Examination of step length and step width, in conjunction with COM data can therefore provide information about balance in the absence of forceplate data before, during and after obstacle crossing. Single and double limb support times provide information on periods of relative instability and stability. Many of these variables are influenced by speed, which is commonly reduced following stroke [3,19], therefore, speed was also controlled in this study.

It was hypothesised that balance would be modified during obstacle crossing in people with stroke, and that several of these adaptations could threaten stability. It was also predicted that some differences observed would be due to reduced walking speed following stroke. Impairment following stroke is frequently asymmetrical, hence balance was quantified when leading with the most affected limb and the least affected limb.

1. Method

1.1. Subject selection

Twelve subjects with a recent cortical or subcortical stroke, capable of walking 10 m without a gait aid or assistance and 12 unimpaired subjects, matched for age (±3 years), sex and height were recruited. Subjects with stroke were receiving rehabilitation for gait or balance disorders. This population is of interest as they utilise the greatest proportion of rehabilitation resources. This was the same sample as tested in Said et al. [4]. Subjects with stroke had a mean age of 65.1 years (S.D. = 16.6), mean height of 169.5 cm (S.D. = 9.4) and were tested a median of 62 days poststroke. Table 1 provides details about subjects with stroke. Unimpaired subjects had a mean age of 64.3 (S.D. = 16.7) years and a mean height of 172.2 cm (S.D. = 9.5). Independent t tests did not detect significant differences between groups for age, height, leg length or weight.

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Age (years)</th>
<th>Lesion site</th>
<th>Days poststroke</th>
<th>Gait speed (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>74</td>
<td>Left internal capsule infarct</td>
<td>15</td>
<td>67.9</td>
</tr>
<tr>
<td>2a</td>
<td>43</td>
<td>Right occipital lobe, frontoparietal cortical infarct</td>
<td>167</td>
<td>45*</td>
</tr>
<tr>
<td>3b</td>
<td>76</td>
<td>No lesion on CT, clinically right lacunae infarct</td>
<td>75</td>
<td>31.3</td>
</tr>
<tr>
<td>3c</td>
<td>74</td>
<td>Right posterior cerebral artery infarct</td>
<td>137</td>
<td>21.4</td>
</tr>
<tr>
<td>4a</td>
<td>42</td>
<td>Left posterior cerebral artery infarct</td>
<td>67</td>
<td>77.9</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>Left frontal hemorrhage</td>
<td>360</td>
<td>74.1</td>
</tr>
<tr>
<td>6</td>
<td>85</td>
<td>Left corona radiata infarct</td>
<td>57</td>
<td>42.3</td>
</tr>
<tr>
<td>7</td>
<td>68</td>
<td>Right frontoparietal infarct</td>
<td>28</td>
<td>62</td>
</tr>
<tr>
<td>8</td>
<td>54</td>
<td>Left putamen hemorrhage</td>
<td>73</td>
<td>82.8</td>
</tr>
<tr>
<td>9</td>
<td>85</td>
<td>Right external capsule stroke</td>
<td>40</td>
<td>48</td>
</tr>
<tr>
<td>10</td>
<td>79</td>
<td>Left occipital infarct</td>
<td>39</td>
<td>52.2</td>
</tr>
<tr>
<td>11</td>
<td>41</td>
<td>Right watershed infarct</td>
<td>51</td>
<td>83</td>
</tr>
</tbody>
</table>

Adapted from Said et al. [4].

* Medical circumstances resulted in incomplete clinical data for subjects 1 and 2. Asterisked results were obtained from the medical history.

† Did not complete testing due to fatigue. No data available for unaffected lead limb over wide obstacles.

‡ Did not lead with the unaffected limb in any trials.

§ An old lesion was detected on CT. No clinical signs.

1.2. Apparatus

A six camera VICON 512®1 three dimensional motion analysis system and a Kistler forceplate2 obtained kinematic and kinetic data. Twenty-one 2.5 cm light reflective markers identified various landmarks on the subject and the obstacle. During obstructed trials a red balsa wood obstacle measuring 4 cm high × 1.5 mm thick × 60 cm long was positioned after the forceplate, approximately 5 m from the starting position. A wide obstacle condition was tested at the same time but is not reported here. Data processing utilised BodyBuilder Version 3.5®1 and Vicon Clinical Manager Version 1.37®1 (VCM) software packages.

1.3. Procedure

Institutional ethics committees’ approvals were obtained and subjects provided informed consent. Data such as lesion site and interval between stroke and testing were collected for subjects with stroke. Additional clinical tests provided descriptive information about subjects’ impairments and level of function and have been previously published [4]. All subjects had corrected binocular visual acuity greater than 6/12 as assessed by an orthoptist.

Subjects wore loose fitting shorts, walking shoes and any prescription eyewear. Anthropometric measures were

2. Performance System 9281B, Kistler Instrumente AG Winterthur, Switzerland.
obtained as outlined in the VCM\textsuperscript{®} manual and used to calculate hip, knee and ankle joints locations [20,21]. Reflective markers were placed on the lower limbs as described in the VCM manual, acromions and obstacle. A static trial, in which knee markers were replaced with knee alignment devices\textsuperscript{1}, allowed the identification of the flexion/extension knee axis and joint centre calculation. A second set of static trials used a custom made triangular device with three markers and a known end point to identify the most distal point of the toe, the heel, and the medial and lateral points of the sole of the shoe [4].

Subjects performed four unobstructed walking trials at comfortable speed. They then performed eight trials for the 4 cm high obstacle and a wide obstacle (not reported). This provided sufficient trials to maximise chances of subjects leading with both limbs. Order of presentation of obstacle condition was counterbalanced and randomly allocated by block. Subjects were instructed to walk at comfortable speed (SSS) and step over the obstacle without contacting it or losing balance. Prior to the trials, subjects visually and manually inspected a replica obstacle and the therapist provided a demonstration. Subjects were reminded to perform the task within their limits of safety and stop if they felt at risk. For safety, subjects were accompanied by a therapist, who walked behind and to the side of the subject, holding the safety belt lightly. Assistance was only provided if required and these trials were not analysed. While the therapist’s presence may have influenced performance [22], this was an ethical requirement because of the risk of falls. To minimise bias, this precaution was also undertaken with unimpaired subjects.

To control for speed, unimpaired subjects repeated the test at a speed matched to their stroke subject counterpart. Subjects were instructed to walk slower, and given feedback after each trial as to whether they had reached the matched speed (MS). No additional instructions were provided. Subjects with stroke performed a maximum number of 20 trials at SSS and unimpaired subjects performed 40 trials (20 at SSS and 20 at MS). As previously reported [4], average gait speed during obstacle crossing was significantly reduced in the subjects with stroke compared with unimpaired subjects at SSS (\(p < .01\)), but not at MS (\(p > .05\)).

1.4. Data processing

For each obstacle condition, one trial leading with the affected limb and one trial leading with the unaffected limb were analysed. The first trials with adequate data (minimal marker loss during the strides of interest and clean forceplate strike, if available) were selected. In 59\% of cases, this trial was the first attempt leading with that limb. To determine whether performance in subsequent trials was systematically influenced by practice or fatigue, differences in spatial and temporal data from two trials (where available, \(n \geq 8\)) were examined. No systematic differences were detected for the subjects with stroke. This supports the validity of using a subsequent trial if the first attempt could not be analysed. Trials were excluded if the subject required assistance to maintain balance. Data were processed using VICON 512\textsuperscript{®} Workstation, VCM\textsuperscript{®} and Bodybuilder\textsuperscript{®} as previously reported [4]. The COP, heel and toe positions were obtained via Bodybuilder\textsuperscript{®}.

Centre of mass was calculated using a seven segment BodyBuilder\textsuperscript{®} model, comprising two thigh, shank and foot segments and a single head, arms and trunk segment. The model was adapted from a 12 segment model developed by Eames et al. [23], which was obtained from the website http://guardian.curtin.edu.au/cga/bodybuilder/index.html on 6 January 2000. Anthropometric data for the trunk segment was obtained from Winter [24] and replaced the head, arms and trunk segments of the original model. The original model and the modified model were compared in three healthy subjects and one stroke subject (not included in this study) while crossing a high and a wide obstacle. Differences between the positions of the COM as estimated by each model were calculated for each subject for each frame. To evaluate the random error associated with the modified model, the standard deviations of the difference scores were calculated [25], and ranged from 1.1 to 3.6 mm in the AP direction and from 0.4 to 3.2 mm in the ML direction. These errors were judged to be small and thus the modified model was used.

Gait speed during obstacle crossing was calculated for each trial from lead heel contact preobstacle to trail heel contact postobstacle in VCM. Instantaneous COM velocity was obtained in BodyBuilder by calculating the central finite difference. Data from BodyBuilder\textsuperscript{®} was saved in ASCII format, and transferred to Microsoft Excel\textsuperscript{®} for further data reduction.

Instantaneous AP COM velocity was examined at five critical phases; lead toe off before the obstacle, lead toe clearance, lead foot contact after the obstacle, trail toe clearance and trail foot contact after the obstacle. Mediolateral COM velocity was quantified by examining peak ML velocity during the crossing stride. The first peak velocity was towards the trail limb and designated as negative. It occurred between trail limb foot contact preobstacle and lead limb toe off. The second peak ML velocity was towards the lead limb and designated as positive. It occurred between lead limb foot contact postobstacle and trail limb toe off.

The AP differences between the COM, COP and BOS, as represented by the stance heel, were calculated at lead toe clearance. Balance is critical during this phase, as the COM is in front of the BOS and there is little time to reposition the lead limb if it contacts the obstacle [8].

Spatial and temporal footstep data were analysed for the step before the obstacle, the crossing step and the step after the obstacle. Step length was measured from heel to heel in the AP direction and step width was measured from heel to heel in the ML direction. Single limb support was the time...
from contralateral foot off to contralateral foot contact. Two double support phases were measured; the first from trail limb foot contact preobstacle to lead limb toe off and the second from lead limb foot contact postobstacle to trail limb toe off.

1.5. Statistical analysis

As Shapiro-Wilks testing determined most data did not differ significantly from a normal distribution ($p > .05$), parametric analyses were used. Since groups were matched for age, gender and height, they were analysed as related samples [26].

As the study aimed to compare performance in subjects with stroke when leading with the affected and unaffected limb with performance in unimpaired subjects, a limited number of planned comparisons were performed [27]. For each comparison, unimpaired subjects were nominated to have an ‘affected’ and ‘unaffected’ limb, in accordance with their yoked stroke subject. The affected limbs of subjects with stroke were compared with the designated ‘affected’ limbs of unimpaired subjects at SSS. The same comparison was then performed for the unaffected limbs. It was predicted that subjects with stroke would have shorter step lengths and longer double support phases than healthy subjects at SSS [28], therefore one-tailed matched pairs $t$ test were performed for those variables. Two-tailed matched pairs $t$ tests were used for planned comparisons involving remaining variables.

Data for trials in which subjects with stroke led with their affected and unaffected limbs were then compared with trials performed by unimpaired subjects at MS. As there were no directional hypotheses for these comparisons, two-tailed matched pairs $t$ tests were performed.

An approach to balance the risk of Type I and Type II errors was adopted. To reduce risk of a Type I error, a Bonferroni adjustment corrected for the four comparisons for each variable, resulting in a significance level of 0.0125. To reduce risk of Type II errors, results between the corrected and uncorrected significance level of 0.05 were interpreted as ‘suggestive of significance, but not definitive’ ([29], p. 7). This allowed identification of areas that could be of interest for future investigation [27].

2. Results

Four subjects with stroke either contacted the obstacle or lost balance on eight out of a total of 186 obstructed trials. One stroke subject led with the affected limb only. Data for one stroke subject were incomplete when leading with the affected limb due to marker loss. As the high obstacle presents a greater challenge to balance than wide obstacles only high obstacle results were reported.

Table 2 presents COM velocity data. Compared with unimpaired subjects at MS, when the affected limb led, COM AP velocity was significantly reduced in subjects with stroke at lead toe off. Reductions suggestive of significance were observed at lead toe clearance and trail foot contact. When the unaffected limb led, results suggested that subjects with stroke were slower at lead toe off but not at other phases. When leading with the affected limb there was a trend for peak ML COM velocity towards the lead limb to be higher following stroke compared to unimpaired subjects at SSS.

Fig. 1 illustrates differences between COM and COP in the AP direction at lead limb clearance. The distance between COM and COP did not differ between subjects with stroke and unimpaired subjects at SSS when leading with either limb, as shown in Fig. 1A ($p > .05$). Compared with unimpaired subjects at MS, subjects with stroke had greater AP distance between COM and COP when standing on the

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Mean (and standard deviation) centre of mass velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lead limb</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Affected ($n = 12$)</strong></td>
<td><strong>Unaffected ($n = 11$)</strong></td>
</tr>
<tr>
<td><strong>Instantaneous AP COM velocity</strong></td>
<td></td>
</tr>
<tr>
<td>Lead toe off</td>
<td>0.73 (0.34)</td>
</tr>
<tr>
<td>Lead toe clearance</td>
<td>0.63 (0.28)</td>
</tr>
<tr>
<td>Lead foot contact</td>
<td>0.86 (0.29)</td>
</tr>
<tr>
<td>Trail toe clearance</td>
<td>0.80 (0.28)</td>
</tr>
<tr>
<td>Trail foot contact</td>
<td>0.81 (0.33)</td>
</tr>
<tr>
<td><strong>Peak ML COM velocity</strong></td>
<td></td>
</tr>
<tr>
<td>Towards trail limb</td>
<td>−0.17 (0.03)</td>
</tr>
<tr>
<td>Towards lead limb</td>
<td>0.18 (0.05)</td>
</tr>
</tbody>
</table>

Note: SSS = self-selected speed, MS = matched speed.

* Different from subjects with stroke, suggestive of significance $p < .05$.

** Significantly different from subjects with stroke $p < .0125$.

*** Significantly different from subjects with stroke $p < .001$. 
affected limb during unaffected lead limb clearance; \( t(10) = 3.166, p = .010 \).

As shown in Fig. 1B, as the affected limb cleared the obstacle, the COM was closer to the unaffected stance heel following stroke, compared to unimpaired subjects at SSS, \( t(11) = 3.912, p = .002 \). Although not significant, this trend continued when subjects with stroke were compared to unimpaired subjects at MS, \( t(11) = 2.077, p = .062 \). During unaffected lead limb clearance the position of the COM relative to the heel did not differ significantly between groups (\( p > .05 \)).

Fig. 1C demonstrates that the COP was also located closer to the unaffected stance heel in subjects with stroke. This was reduced significantly compared to unimpaired subjects at SSS, \( t(10) = 4.975, p = .001 \) and suggestive of significance when compared at MS, \( t(10) = 2.974, p = .014 \). During affected limb stance, the position of the COP relative to the heel did not differ between groups at either speed (\( p > .05 \)).

Spatial and temporal characteristics are reported in Table 3. Compared with unimpaired subjects at MS, subjects with stroke reduced step length before and after the obstacle when leading with both the affected and unaffected limb. Crossing step lengths did not differ between subjects with stroke and unimpaired subjects at MS.

Double support was increased in subjects with stroke compared with unimpaired subjects at SSS when leading with either limb, but not at MS. Single limb support was increased during affected lead limb clearance following stroke compared with unimpaired subjects at SSS.

3. Discussion

Subjects with stroke made several modifications to balance that may have enhanced safety during obstacle crossing. As expected, their COM AP velocity was slower than unimpaired subjects walking at SSS, and could relate to impairments, such as reduced muscle strength or power [30] as well as impaired balance. Of interest were differences detected when comparisons were made with unimpaired subjects at MS. When subjects with stroke led with their affected limb, the COM AP velocity was significantly slower at lead toe off and tended to remain reduced at lead toe clearance. This might be related to reduced push off and propulsion on the affected limb, but it may also assist safety during affected lead limb clearance. If the swing foot had inadvertently contacted the obstacle, corrective action would be required to reposition the foot and avoid a fall. Decreasing COM AP velocity would reduce the anterior movement of the COM, making it easier to regain stability and reducing the chance of a fall in the forward direction [14,31]. Positioning the COP closer to the unaffected (stance) heel, which could indicate reduced activation in the plantar-flexors, is also in keeping with reduced AP velocity [32–34].

There may also be safety advantages in positioning the COM closer to the stance heel, which was observed when subjects led with the affected limb, but not with the unaffected limb (Fig. 1B). Keeping the COM more posterior would increase the anterior margin of stability [13,14], minimising forward instability if the affected lead limb contacted the obstacle. Regulation of both COM position
and velocity might be adaptive to ensure balance is maintained when crossing an obstacle with the affected limb.

Several findings indicate that subjects with stroke had difficulty controlling balance. When the lead limb cleared the obstacle, no differences in the AP distance between COM and COP were detected between groups at SSS (Fig. 1). Nevertheless, when comparisons were made at MS, subjects with stroke had their COM further in front of the COP when standing on the affected limb. This indicates they had greater forward acceleration of the COM as the unaffected toe cleared the obstacle, which may indicate greater instability compared to unimpaired subjects walking at MS. Subjects with stroke could have difficulty controlling COM and COP position during affected limb stance. The reduced speed utilised following stroke might ensure that separation between COM and COP remains within acceptable limits required to maintain balance. This suggests that reduced gait speed following stroke could partly be compensation for poor balance.

Smaller step lengths in subjects with stroke compared with unimpaired subjects at MS may place them at risk of losing balance and falling. A smaller step length would position the COP closer to the COM at initial foot contact, reducing the braking force. The impact on stability is partly dependent on the instantaneous velocity of the COM in the AP direction and limb swing time (contralateral single limb support time). Step length reduction before the obstacle following stroke might not threaten balance. Compared with unimpaired subjects at MS, subjects with stroke had slower velocities before obstacle crossing (Table 2) and may be able to produce sufficient braking force to control the AP COM velocity. The reduced step length in the subjects with stroke after crossing the obstacle could, however, threaten stability. Compared with unimpaired subjects at MS, there was a relatively large and significant reduction in step length, while reductions in instantaneous COM AP velocity and swing time were small and not significant. This may have placed subjects with stroke at risk of losing balance forwards in steps after obstacle crossing.

It is possible that the reduction in step length after obstacle crossing was the re-establishment of the unobstructed walking pattern in subjects with stroke. To explore this, post hoc inspection of unobstructed data was performed. Compared with unimpaired subjects at MS, subjects with stroke had shorter step lengths; affected limb; \( t = 2.261, p = .047; \) unaffected limb; \( t = 2.464, p = .032. \) However, in the first step after obstacle crossing, while step length was reduced in the people with stroke, no reduction in step time was detected (\( p > .05. \)) The reduction in step length after the obstacle could represent re-establishment of the gait pattern, but as the temporal relationship is not yet re-established, stability may be compromised.

Subjects with stroke might have had difficulty controlling balance in the ML direction. When leading with the affected limb, there was a trend for peak ML velocity to be increased towards lead and trail limbs following stroke compared with unimpaired subjects at SSS, which may indicate poor balance in the ML direction. Higher velocities could reflect difficulty decelerating the COM, which is governed during double support by the relative loading and unloading of the two limbs.
Examination of COP under both feet during double support is required to understand control of COM and COP during obstacle crossing. No other variables measuring ML balance were able to detect differences between groups. This is preliminary data on balance deficits during obstacle crossing in people with stroke undergoing rehabilitation. It is acknowledged that the use of only one trial with each limb per subject is a methodological limitation of the study. While use of more trials would be desirable, this was precluded by several factors: (1) limitations on the number of trials to avoid fatigue, (2) not dictating with which limb subjects led and (3) missing data. Also, the therapist’s presence may have impacted on performance. Bias was minimised by following the same procedure with both groups and excluding trials where assistance was provided. Despite limitations, results provide a scientific foundation for further development of gait rehabilitation strategies and a basis from which to answer other clinically important questions.

4. Conclusion

Balance during obstacle crossing was compromised following stroke. Subjects with stroke may be unstable during affected limb support compared with unimpaired subjects, as indicated by greater separation between the COM and COP. When leading with the affected limb, threats to balance could have been minimised by reducing speed and maintaining the COM closer to the support heel. Smaller steps after obstacle crossing might have placed individuals at risk of losing balance forwards.

Acknowledgements

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References


[34] Neptune RR, Kautz SA, Zajac FE. Contributions of the individual ankle plantarflexors to support, forward progression and swing initiation during walking. J Biomech 2001;34:1387–98.